TITLE: Terahertz Spectral Analysis by Frequency-Selective Incoherent Detection in High-T[c] Josephson Junctions

Terahertz Spectral Analysis by Frequency-Selective Incoherent Detection in High-T_c Josephson Junctions

Yuri Divin, Ulrich Poppe, Knut Urban, Oleg Volkov, Valery Pavlovskii

Abstract — **The detector response of $YBa_2Cu_3O_{7-x}$ Josephson grain-boundary junctions to monochromatic radiation with the frequency f in the range from 60 GHz to 5 THz has been studied. Odd-symmetric resonances near the voltages $V=hf/2e$ in the responses $\Delta I(V)$ of these junctions to radiation with different frequencies f have been observed in a decade of spectral range for any operating temperature between 30 to 85 K. The spectral range of this selective detection has scaled with the I_cR_n-product of the Josephson junction, so decreasing the junction temperature from 85 to 30 K one can perform the spectral analysis in two decades. A prototype of terahertz Hilbert-transform spectrum analyzer based on high-T_c Josephson junction integrated into a Stirling cooler has been developed. A resolving power $\delta f/f$ of around 10^{-3} has been demonstrated in the spectral analysis of output radiation from optically-pumped far-infrared CH_3OH laser.**

I. Introduction

One of the promising applications of superconducting junctions is the detection of electromagnetic radiation. Among them, the detectors using the ac Josephson effect can give an information on the spectrum of incident radiation [1]. A frequency-selective detection takes place in Josephson junctions due to an interaction of internal voltage-controlled Josephson oscillations and external signals. The corresponding detectors based on low-T_c Josephson junctions have been studied earlier [2-5], and only after some progress in junction fabrication, the first evaluations of high-T_c Josephson junctions for this application have been carried out [6-8]. Recently, we have demonstrated a selective Josephson detection in a decade of the spectral range with the highest frequency of 3.1 THz [9].

Frequency-selective Josephson detection of electromagnetic radiation is the basic principle of Hilbert-trasform spectral analysis [1]. Spectral measurements of millimeter- and submillimeter-wave radiation by Hilbert-transform technique have been carried out using both low-T_c and high-T_c Josephson junctions [1, 10-16]. The laboratory prototypes of Hilbert-transform spectrometers and spectral analyzers cooled by cryogenic liquids have been developed [1,11,13,16].

A necessity to use cryogenic liquids for cooling is considered as a main obstacle on the way of superconducting electronics into the market, and a replacement of them by cryocoolers is required [17]. Here, we report on the characteristics of a Hilbert-transform spectrum analyzer based on high-T_c Josephson detector integrated into a Stirling cooler.

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II. Theory

In the simple resistively shunted junction (RSJ) model [18], the response $\Delta I = I(V) - I_0(V)$ of a Josephson junction to weak monochromatic radiation with the frequency f is equal to [18]

$$\Delta I(V) = I_s^2\left(\frac{2e}{h}\right)\frac{I_c^2R_n^2}{8I_0V}\left[\frac{(f_j+f)}{(f_j+f)^2+\left(\frac{\delta f}{2}\right)^2}+\frac{(f_j-f)}{(f_j-f)^2+\left(\frac{\delta f}{2}\right)^2}\right], \quad (1)$$

where I_c is the critical current of the junction, R_n is the normal-state resistance of the junction, I_s – is the amplitude of the radiation induced current ($I_s<<I_c$), I_0 is the dc current flowing through the junction, $V=R_n(I_0^2-I_c^2)^{1/2}$ is the voltage across the junction, $f_j=2eV/h$ is the voltage-controlled frequency of internal Josephson oscillations and δf is the Josephson oscillations linewidth.

The response $\Delta I(V)$ (Eq. 1) is quadratic with the signal amplitude I_s. At low voltages $V<<hf/2e$ in the limit of small δf, the response $\Delta I(V)$ approaches the value

$$\Delta I_0 = -(I_s^2R_n/2)(2e/h)(f_c/2f^2), \quad (2)$$

where $f_c=(2e/h)I_cR_n$ – is a characteristic frequency of the Josephson junction. This low-voltage response is actually a suppression of the critical current of the junction by external radiation.

At the voltages V, where the Josephson frequencies f_j are close to the frequency f of the incident radiation, the response $\Delta I(V)$ shows an odd-symmetric resonance. The maximum amplitude ΔI_{max} of this resonance at $V=(h/2e)[f+(\delta f/2)]$ is inversely proportional to the Josephson linewidth δf:

$$\Delta I_{max} = (I_s^2R_n/2)(2e/h)[f_c^2/4(f_c^2+f^2)^{1/2}f\delta f]. \quad (3)$$

For broadband thermal fluctuations with a noise temperature T and $kT<eV$ (equilibrium case), the Josephson linewidth is equal to [18]

$$\delta f = 4\pi(2e/h)^2kT(R_d^2/R_n)\left[1+\left(I_c^2/2I_0^2\right)\right], \quad (4)$$

where R_d is the dynamic resistance of the junction. The dynamic resistance $R_d(V)=dV/dI=R_n(V^2+I_c^2R_n^2)^{1/2}/V$ is

equal to the normal-state resistance R_n at high voltages $V>I_cR_n$, and at small voltages $V<I_cR_n$ it is inversely proportional to the voltage. So, the linewidth and the width of the odd-symmetric resonance in the response $\Delta I(V)$ (Eq. 1) will decrease with the increase of the frequency f at low frequencies $f<f_c$ and will be frequency independent at high frequencies $f>f_c$.

One can expect from Eq. 3 and Eq. 4, that the amplitude ΔI_{max} of the selective response should rise linearly with the increase of the frequency f at low frequencies $f<f_c$, reach a maximum at $f\sim f_c$ and fall down inversely proportional to $f^{\,2}$ at high frequencies $f>f_c$. This conclusion is valid, provided the same current amplitudes I_s are induced by radiation with different frequencies f. But, due to the different power level of the radiation sources and frequency-dependent coupling of radiation to the junction, the requirement of a constant I_s is difficult to fulfill experimentally.

We have solved this problem by a selfcalibration procedure, when we normalize each of the measured response curves $\Delta I(V)$ to its value ΔI_0 (Eq. 2) at low voltages [5]. The maximum amplitudes ΔI_{max} of the resonances in these normalized responses are proportional to $f^{\,3}$ at low frequencies $f<f_c$ and independent of the frequency at high frequencies $f>f_c$. The last circumstance just reflects the frequency-independent behavior of the amplitude of Josephson oscillations in the RSJ model. With this normalization, each set of data can be compared with the others, measured for different frequencies, and deviations from the RSJ-behavior can be easily detected.

The Josephson junctions which are close to those of predicted by RSJ model are good candidates for the Hilbert-transform spectral analysis [1]. Within the framework of the resistively-shunted-junction (RSJ) model, the small-signal response $\Delta I(V) << Io(V)$ was calculated for radiation with an arbitrary spectrum, inducing currents through the junction with the spectral density $S_i^2(f)$. The calculated response $\Delta I(V)$ with the accuracy of smooth experimentally measured functions was found to be proportional to the Hilbert transformation of the spectral density $S_i^2(f)$, so the unique deconvolution of $S_i^2(f)$ from the experimental data is possible. The exact solution of the problem was found to be [1]

$$S_{i^2_j}(f)=\left(\frac{1}{\pi}\right)\cdot\int_{-\infty}^{+\infty}\frac{H(f_j)}{(f_j-f)}\cdot df_j \qquad (5)$$

where $f_j = 2eV/h$ is the voltage-controlled frequency of the Josephson oscillations, $H(V)$ is a normalized response function

$$H(V)=(8/\pi)(h/2e)[\Delta I(V)I(V)V/I_c^2R_n^2]\,, \qquad (6)$$

consisting of the product of the response $\Delta I(V)$, the current-voltage characteristic $I(V)$ and the voltage V. I_c is the critical current and R_n is the normal-state resistance of the Josephson junction. The principal value of integral should be taken in Eq. 1. So, to get spectrum of radiation, one should measure the $I(V)$ - curve of Josephson junction, its response $\Delta I(V)$ to this radiation and perform the Hilbert transformation of normalized response function $H(V)$. Actually, the spectral resolution of HTS is determined by the linewidth δf of the Josephson radiation (Eq.4).

III. EXPERIMENT

A laboratory prototype of spectrum analyzer based on high-T_c Josephson junction has been developed. A frontend of this analyzer is shown in Fig. 1. High-quality $YBa_2Cu_3O_{7-x}$ grain-boundary junctions fabricated on untwinned 2x14° (110) $NdGaO_3$ bicrystal substrates [19] have been used in the experiments. The widths of the junctions were in the range 1-3μm. The I_cR_n-products of these junctions were up to 330 μV at 78 K, and the values of resistances R_n varied from 1 to 8 Ohm. A broadband $YBa_2Cu_3O_{7-x}$ log-periodic antenna has been integrated with each junction on the substrate.

The substrate with the Josephson junction was mounted in a vacuum chamber on the coldfinger of a Stirling cooler [20]. Junction temperatures in the range from 30 to 90 K have been achieved in this cryogenic environment. The measurements at any of these temperatures could be carried out during several hours with a reasonable drift of 1-2 K. The compressor of the Stirling cooler and the vacuum chamber were magnetically shielded by several layers of mu-metal foil.

An optically-pumped far-infrared laser and a backward-wave oscillator with a multiplier were used as sources of monochromatic radiation in this study. With this combination we were able to deliver radiation in the

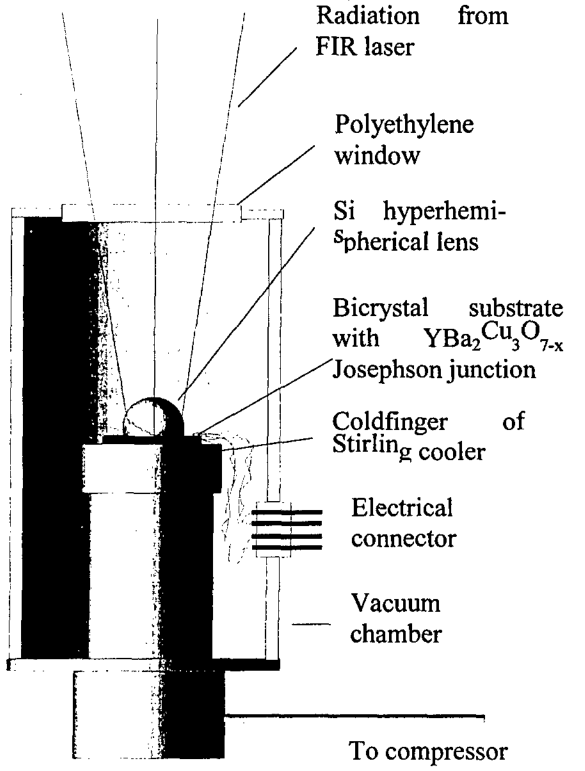

Fig. 1. Frontend of terahertz spectrum analyzer based on high-Tc Josephson junction integrated into a Stirling cooler.

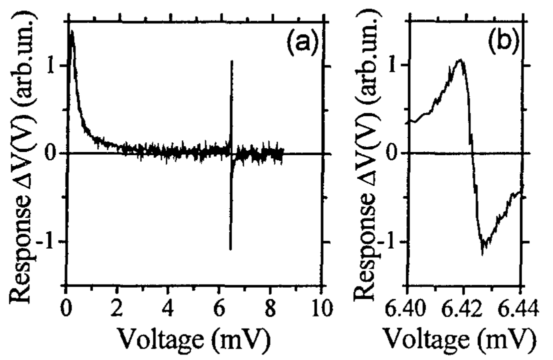

Fig. 2. a) The response $\Delta V(V)$ of $YBa_2Cu_3O_{7-x}$ bicrystal Josephson junction to far-infrared laser radiation with the frequency of 3.106 THz. b) The same response near the resonance at the voltage V=6.423 mV. The junction resistance R_n= 1 Ohm and the temperature T = 34 K .

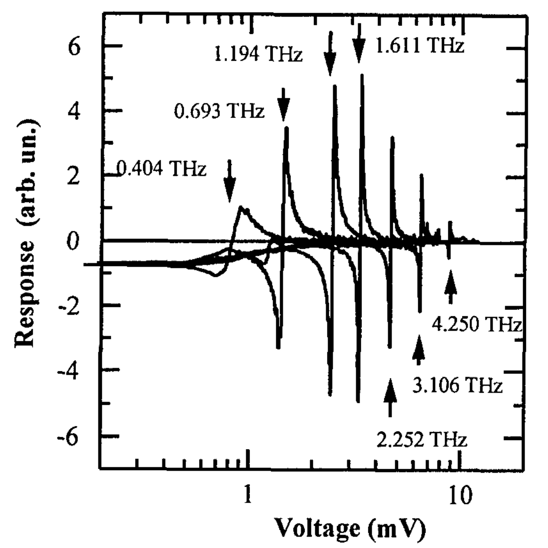

Fig. 3. Normalized responses $\Delta I(V)/\Delta I_0$ of the $YBa_2Cu_3O_{7-x}$ Josephson junction to monochromatic far-infrared radiation with different frequencies. The junction resistance R_n = 7 Ohm and the temperature T =34 K.

frequency range from 60 GHz to 5 THz. Absorption attenuators were placed between the radiation sources and the Josephson junction to guarantee a low level of radiation for square-law detection by the Josephson junctions. Radiation was focused to the junction antenna by a parabolic mirror through a polyethylene window in the vacuum chamber and a hyperhemispherical Si-lens on the substrate (Fig. 1).

IV. Results

The response $\Delta V(V)$ of a $YBa_2Cu_3O_{7-x}$ Josephson junction to 3.1 THz radiation is shown in Fig. 2 [9]. The Josephson junction has a resistance of R_n = 1 Ohm and quite high I_cR_n-product of 1.5 mV at 34 K. The shape of the response $\Delta V(V)$ (Fig. 2a) is very close to that of the RSJ model in the voltage range from 0 to 8.5 mV. The response ΔV demonstrates a very sharp odd-symmetric resonance around the voltages near $V = hf/2e$ = 6.423 mV. The width of this resonance is around 8 μV (Fig. 2b), which corresponds to the Josephson linewidth δf of 3.9 GHz. So, it follows from the measured response that a resolving power $\delta f/f$ of the order of 10^{-3} might be achieved with selective detection by high-T_c Josephson junctions.

To obtain a normalized response $\Delta I(V)/abs(\Delta I_0)$, as it was discussed in the introduction, the current response $\Delta I(V)=-\Delta V(V)/R_d(V)$ was calculated and the value of ΔI_0 was determined by extrapolation of the low-voltage behavior of $\Delta I(V)$ to V=0. A set of the normalized current responses $\Delta I(V)/abs(\Delta I_0)$ of a Josephson junction with R_n = 7 Ohm to monochromatic signals with the frequencies from 0.404 THz up to 4.25 THz are shown in Fig. 3. With an increase of frequency f, the amplitude of the odd-symmetric resonances at $V=hf/2e$ also increases, then, when the frequency is around $2f_c$ (and the voltage is around $2I_cR_n$), reaches the maximum, and falls down with further increase of frequency.

For each temperature in the range of 30 – 85 K the selective response is observed at least in one decade of frequency bandwidth [9]. The middle frequency of this bandwidth scaled with the characteristic frequency $f_c=(2e/h)I_cR_n$, so the total bandwidth of selective detection, which was covered by one Josephson junction at different temperatures, was around two decades.

The low-frequency cut-off of the appearance of the resonances in responses $\Delta I(V)/abs(\Delta I_0)$ in Fig. 3 is in accordance with the RSJ behavior. It is the result of the low-voltage increase of the linewidth of Josephson radiation and a corresponding decrease of the resonance amplitude according to Eq.3. The high-frequency fall-down of the selective response was attributed to Joule heating [9] and it might be shifted to higher frequencies by increasing the junction resistance and/or further decreasing the operation temperature. As we can see from Fig.3, the increase of the resistance to 7 Ohm results in the increase of highest frequency to 4.25 THz. In the case of high-ohmic junctions the high-frequency cut-off might be also due to capacitive shunting of the junction.

V. Application

An example of application of the developed Hilbert-transform spectrum analyzer is demonstrated in Fig. 4. Radiation to the spectrometer came from a far-infrared CH_3OH laser, pumped by 9P36 line of CO_2 laser. The length of the FIR laser cavity was slightly changed from one position (a) to the other (b). In the case (a), two odd-symmetric resonances appeared at the response $\Delta I(V)$ of the spectrometer. An application of Hilbert-transformation to the normalized response $\Delta I(V)\cdot I(V)\cdot V$, according to the Eq.5, gives the spectrum of incident radiation. Two lines, the main at 2.523 THz and the competing one at 1.758 THz, are clearly visible in the spectrum. The intensities of laser lines are inside the dynamic range of the spectrum analyzer and no artificial line at the difference frequency has appeared in the spectrum. Changing the length of

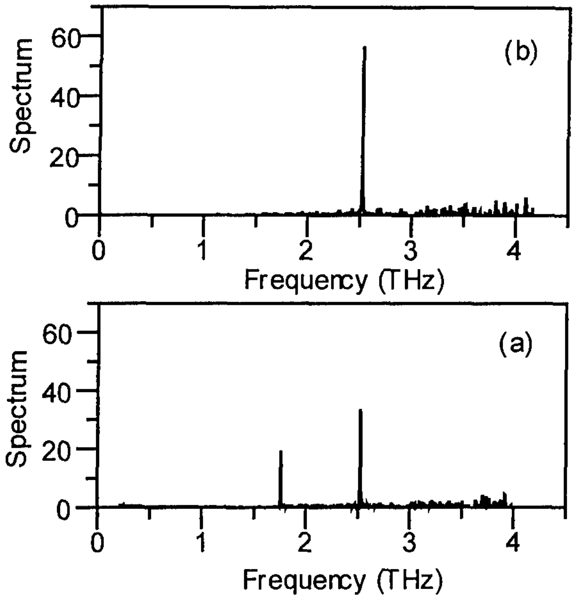

Fig. 4. Spectra of radiation from optically-pumped CH_3OH laser recovered by Hilbert-transform spectrum analyzer. The pump line of CO_2 laser is 9P36. Spectra (a) and (b) have been measured for different lengths of laser cavity.

laser cavity and controlling the spectrum of laser radiation it is possible to get a single-line operation of the optically pumped laser (b). The measurement time of around 10 seconds has been achived with this analyzer.

VI. Conclusion

We have demonstrated a decade bandwidth of the selective detection of terahertz radiation by $YBa_2Cu_3O_{7-x}$ Josephson junctions for any junction temperature in the range of 30 - 85 K. The bandwidth scaled with the I_cR_n-product of the junction, and using one junction at different temperatures one can cover up to almost two decades with a selective detection. A prototype of Hilbert-transform spectrum analyzer have been developed based on high-T_c Josephson detector integrated into a Stirling cooler. An application of this spectrum analyzer for optimization of single-line operation of far-infrared optically-pumped CH_3OH laser has been demonstrated. Broadband operation of Hilbert-transform technique [1] in the terahertz range with a resolving power of around 10^{-3} might be achieved according to these experiments.

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